Control of Posture, Subjective Vertical, and Body Scheme in Changing Gravitoinertial Field

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Summary

Spatial disorientation associated to decrease of sensorimotor performance may result in observers evolving in changing gravitoinertial field as created in aircrafts and other high dynamics modern vehicles. We have investigated the influence of body support orientation on the perception of egocentric and exocentric reference frames in 8 observers standing 80 cm off-center on a platform rotating at 120 deg.s^{-1}. Standing support was either a fixed horizontal board or a swinging pendulum. The perceptive task consisted in adjusting the orientation of a visual rod to indicate geocentric (subjective vertical (SV) and horizontal (SH)) and egocentric (head, trunk and platform orientations) references. Subjects' head and trunk, as well as rod orientations, were recorded with electromagnetic sensors (Polhemus Fastrack). The platform was equipped with sensors providing heel and toe vertical and lateral forces from both feet. Platform motion (when allowed to rotated in the swinging pendulum condition) was recorded with a potentiometer. We analyzed body postural reactions and compared veridical and perceived orientations in the two body support conditions.

In the horizontal platform condition, to compensate the mechanical constraints caused by the centrifugal force, subjects leaned toward the axis of rotation adopting a hyperbolic body shape. Head was aligned with the gravitoinertial force. SH was not sensed as orthogonal to the SV. Foot pressure (vertical and lateral components) was higher under the outer than under the inner foot. In the swinging pendulum condition, SV and body were aligned with the gravitoinertial vector. SH and SV were orthogonal. Foot pressure was the same under both feet. In both conditions, head and body orientations were overestimated. The data suggest that, as the gravitoinertial vector evolves, the vestibular system induces compensatory postural adjustments. The hyperbolic body shape is thought to be due to body multisegmental coordination. Other postural adjustments, thought to be neither of vestibular nor of visual origin, occur to keep the projection of the combined forces in the body support area. Although observers provided erroneous cognitive answers, they maintained postural balance in both conditions suggesting sensorimotor control to be independent of posture related cognitive processes.

Introduction

Mechanisms which govern the control of posture are still misunderstood. The human erect posture serves two main functions (Massion, 1994): on the one hand, posture counteracts the action of gravity by maintaining the body center of mass projection inside the supporting surface. On the other hand, posture constitutes an egocentric reference for perception and action, which partly depends on gravity, seen as a geocentric reference.

Human activities evolve under the influence of the gravitational field. Self generated movements as well as movements which human beings are submitted to (acceleration in vehicles, bends…) mainly product inertial and Coriolis forces. Inertial forces combine with gravity and generate gravitoinertial changes. To maintain balance during gravitoinertial changes, the axis linking the body center of pressure with the body center of mass must be kept aligned with the gravitoinertial vector. The gravitoinertial vector becomes then the new geocentric reference which must be used to maintain posture, instead of gravity.

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Several sensory information contribute to the control of posture (visual, proprioceptive, tactile, and vestibular information). But spatial disorientation generally occurs when subjects are deprived of visual references. Without any visual information, the control of posture mainly relies on a vestibular-somesthetic interaction (Mergner & Rosemeier, 1998). This vestibular-somesthetic interaction also participate to awareness perception of space and body orientation. The gravitoinertial vector direction and the support orientation constitute two major parameters of the environment constraints for postural control in darkness. Indeed gravitoinertial vector direction and body support orientation directly act on sensory inputs by modifying the ground reaction forces direction. It follows that, in this context, posture as well as perception would be modified.

The purpose of the present study was to determine the role of the support orientation in posture and perception when the gravitoinertial field is modified. We used a rotating platform to modify the gravitoinertial field. Two kinds of support were use: a fixed horizontal support (presenting discongruent sensory information during rotation) and a free pendulum support which tilted with the gravitoinertial vector (GIV) so that the support orientation was always approximately perpendicular to the GIV during rotation (sensory information were congruent).

Methods

Subjects

Eight healthy male subjects without vestibular or balance problem took part in the experiment (mean age : 24.12 ± 1.6 years old, mean weight : 71.62 ± 4.40 kg, mean height: 178.73 ± 2.44 cm). They gave informed consent to participate to this study.

Procedure and task

The experiment took place in darkness. Subject were standing head-front on a rotating platform, 80 cm from its vertical rotation axis (Fig. 1). A luminous rod was placed at eye level in front of the observer. Rod orientation could be adjusted by means of a joystick held manually. The behavioral task was to maintain postural equilibrium during platform rotation. The cognitive task consisted in adjusting the luminous rod to successively provide readings of 1- subjective vertical, 2- perceived body orientation, 3- perceived head orientation, 4- subjective horizontal and 5-perceived platform orientation.

The cognitive task was performed before, during, and after rotation on either a horizontal support, fixed with respect to the rotating shaft (Fixed condition) or on a pendulum support free to oscillate about a sagittal axis (Free condition), placed 30 cm above the subject's center of mass.

Subjects performed the tasks first when the platform was still motionless then when the platform was set into motion. During the acceleration phase which lasted 90 s and carried the platform at 120°.s^{-1} (GIV was then tilted by 19.7°), subjects were only asked to maintain their equilibrium. During the constant velocity phase which lasted 240s, subjects were asked to perform the cognitive task, starting 60s after the platform reached constant velocity (that is after semicircular canals returned to their resting state). Subjects' task was again to maintain equilibrium during the 90s deceleration phase. A final cognitive task was then executed 60s after the platform was stopped. Subjects were submitted to 4 rotation sequences for each support condition.

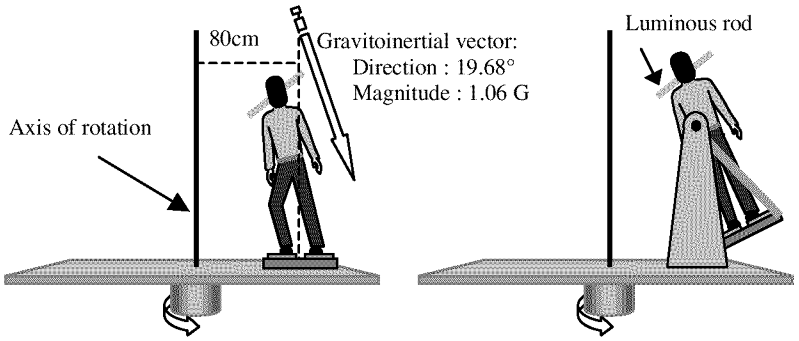

Fig. 1: Back view of a subject standing off-center on the rotating platform in the two experimental support conditions during rotation at constant velocity. Left drawing illustrates the fixed horizontal support condition and right drawing illustrates the free pendulum support condition.

Behavioral recordings

A strain gauge posturograph was used to monitor vertical and lateral forces applied under the subject's front and back of each foot. Head, trunk, and rod orientations were monitored by means of an electromagnetic movement device (Polhemus Fastrack). A potentiometer measured the free-pendulum support orientation in space.

Data analysis

Mean vertical and lateral forces as well as statokinesigrams were used to describe postural strategy and stability. The gravitoinertial vector applied at head level was calculated and used as the current geocentric reference. Head, body, platform veridical orientations were compared to subjective values provided by corresponding rod orientations. An Analysis of Variance assessed the significance of the differences between the experimental conditions. A post hoc test (Newman-Keuls) showed the specific differences. Null hypothesis were rejected when probabilities were below the threshold of 0.01.

Results

All subjects were able to execute postural and cognitive tasks in both support conditions, although they reported more difficulties to maintain postural equilibrium in the free-pendulum than in the fixed-support condition. The data corroborate subjects' reports. Comparison of postural and perceptual data collected before and immediately after rotation showed no significant differences ($p>.05$) thus demonstrating no after-effect. Consequently, these results will not be further commented.

Postural stability and force repartition

Fig. 2 illustrates vertical and lateral forces repartition between the two feet in the two support conditions during rotation. Results showed that during the rotation, subjects used a postural strategy specific to the support. In the Fixed condition, subjects tilted their body inwards by bending the inner leg and keeping straight the outer, to compensate for the centrifugal force. Vertical forces were significantly greater under the outer foot (73.04% ± 1.5 of the whole body weight, versus 26.96% ± 1.53 under the inner foot ($p<.01$)). The lateral forces were also significantly greater under the external foot (26.3% ± 0.46) than under the internal foot (8.35% ± 0.34) ($p<.01$).

In the Free condition, subjects kept the two legs straight. Vertical forces under the feet were still significantly different (Mean force under the inner foot: 55.03% ± 12.56; the outer foot: 44.97% ± 12.55; $p<.01$). Lateral forces were low under each foot but significantly greater under the inner foot (3.85% ± 0.73) than under the outer foot (1.04% ± 0.45) ($p<.01$).

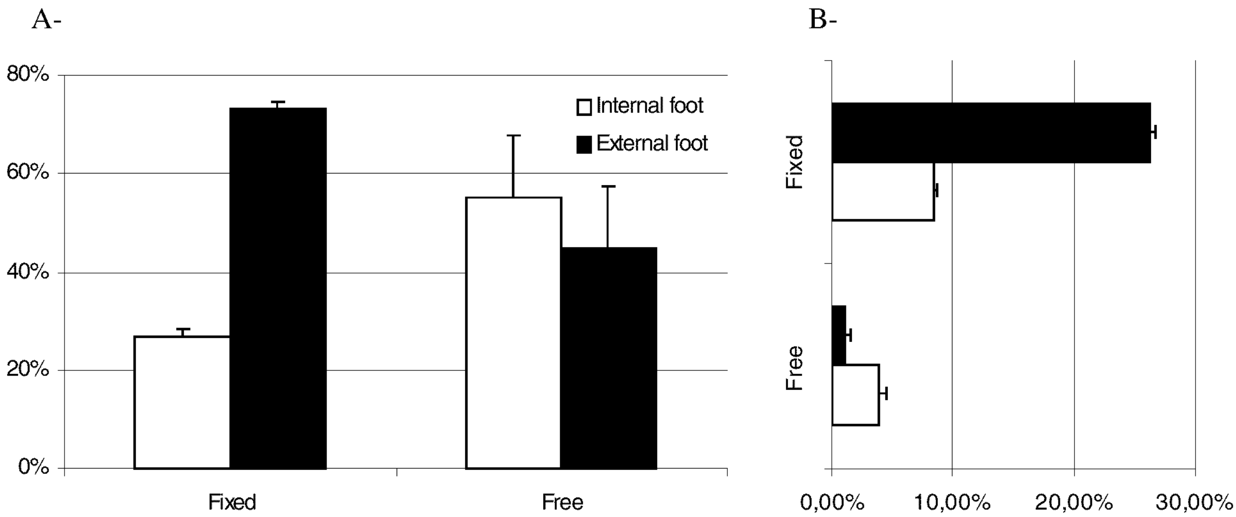

Fig. 2: Mean vertical (A) and lateral (B) forces which applied under each foot in the two support conditions during rotation. Whereas vertical forces are expressed in percentage of body weight, lateral forces are expressed in Newton.

Veridical orientation versus perceived orientation

During rotation in the Fixed condition, subjects' head tilted by 5.59° ± 0.88 inwards and was significantly different from head position before rotation (p<.01) and body tilted by 7.66° ± 4.3 inwards. The GIV acting at subjects' head level tilted by 13.43° ± 0.96 inwards. This vector was taken as the new geocentric reference to determine veridical vertical and horizontal during rotation.

Subjects perceived their head as tilted by 10.93° ± 9.15 inwards. Moreover, they perceived their body as being tilted by 14.9° ± 5.55 inwards. Vertical was perceived as tilted by 7.56° ± 4.5 inwards and horizontal as tilted by 4.7° ± 2.73 inwards. Subjects perceived the platform as tilted by 4.14° ± 9.15 inwards.

The post-hoc test revealed that the GIV and the subjective vertical differed significantly (p<.01). Moreover, subjective horizontal significantly differed from the axis perpendicular to the GIV (p<.01). Subjective vertical and subjective horizontal were not perpendicular in this support condition (p<.01). In addition, subjects significantly overestimated their head and body tilts (p<.01). However, there was no significant difference between the real and perceived platform orientations (p>.05).

During rotation in the Free condition, subjects' head and body tilted by 19.21° ± 1.84 inwards and 23.26° ± 4.7 inwards, respectively. The GIV tilted by 17.56° ± 0.91 inwards and the platform tilted by 26.7° ± 1.18 inwards.

Subjects perceived their head and their body as tilted by 23.28° ± 4.4 inwards and by 24.13° ± 2.9 inwards, respectively. They perceived the vertical and the horizontal as tilted by 16.1° ± 5.32 and by 15.17° ± 7.82 inwards, respectively and the platform as tilted by 23.22° ± 8.21 inwards.

The ANOVA revealed that there was no significant difference between veridical and perceived values in the Free condition (F(1,29)=0.24287 ; p>.05).

Comparison of the 'perception error' (defined as the difference between veridical and perceived values, Fig. 3) in the two support conditions showed that error in estimating the geocentric reference (vertical and horizontal) was significantly lower in the Free condition (p<.01). In the Free condition, vertical and horizontal were perceived as being orthogonal (p>.05). Subject correctly estimated their body orientation (p>.05). However the head tilt was still overestimated (p<.01).

To summarize, during rotation in the Fixed condition, subjects underestimated the tilt of the geocentric references (gravitoinertial vertical and horizontal). In addition, they overestimated their head and body tilts. The estimation of the platform orientation was not significantly different from its actual orientation.

In the Free condition, subject correctly estimated the orientation of the geocentric references as well as platform and the body orientation. but subjects still overestimated their head tilt.

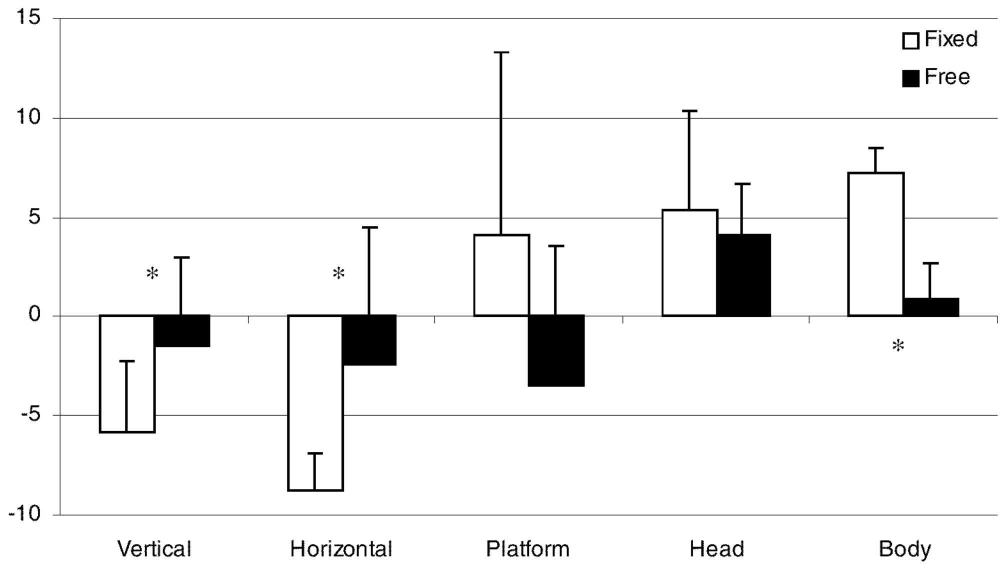

Fig. 3: Mean values of 'perception errors' (difference between veridical and perceived reference values) for the geocentric and egocentric references in the two support conditions during rotation.

Discussion

The purpose of this study was to determine cognitive and postural responses of subjects submitted to changes in gravitoinertial forces while standing on a fixed or on a free oscillating support without any environmental visual reference. In spite of the difficulty of the task, all subjects maintained their equilibrium and performed the perceptive task during rotation.

Rotation induced no after-effect on posture and perception. Before and after rotation, subjects perceived the different references with accuracy. This result differed from what Kaufmann et al. found in 2001. Indeed, they showed that subjects, after being exposed to gravitoinertial changes during 90 minutes, reported that they felt tilted in the direction opposite to the GIV after rotation. Moreover, there was an increase in the displacement frequencies of the center of pressure. The long period of rotation as well as the higher magnitude of the GIV (1.4G) used in their experiment might explain the presence of such an after-effect.

Concerning the postural responses, subjects used two postural strategies specific to support condition. During rotation on the fixed horizontal support, subjects' inner leg was bent as outer stretched. The body curved inwards (still remaining in a sagittal plane) to ensure the antigravity function. The postural forces (vertical and lateral) were mainly applied by the outer leg. On the free pendulum support, subjects kept their two legs straight and the forces were more balanced between the two feet. Some subjects reported to have applied more force under the inner foot in order to immobilize the free pendulum against its mechanical stop. This could explain the increase in the standard deviations we observed in the latter condition.

Concerning the perceptive responses on the fixed horizontal support, geocentric references were underestimated, in particular the subjective horizontal. Subjects overestimated their body tilt as well as their head tilt. The estimation of platform orientation showed great variability. However, when subjects were standing on the free pendulum support, they perceived geocentric values as well as body orientation with more accuracy. Riccio et al. (1992) found similar results for the perception of vertical by dissociating the orientation of the gravitoinertial forces from the orientation of the ground reaction forces, with the RATS (Roll-Axis Tracking simulator). Indeed, they found that the orientation of the subjective vertical depended on both gravitoinertial force direction and ground reaction forces direction needed to control balance. Our results allow us not only to extend the influence of the force orientation to the geocentric references (subjective vertical and horizontal), but also to show that ground reaction forces seem to influence more the subjective horizontal than the subjective vertical. Our results suggest that the visual subjective horizontal is not likely to be inferred from the visual subjective vertical but would depend more on the interaction between body and support. On this point of view, the congruence between sensory information become a major component to perceive the geocentric references as orthogonal. Thus, support orientation played an

important role in the perception of spatial orientation. It influences the perception of geocentric references as well as perception of body orientation. However in our experiment, perception of head orientation was not influenced by the support orientation. According to Mergner & Rosemeier (1998), head orientation in space would be directly estimated from the GIV direction, whereas body orientation in space would be rebuilt from support orientation in space and body orientation on support. Several authors showed that the perception of egocentric references were less accurate than the perception of geocentric references (e.g. Darling & Hondzinski, 1999).

To conclude, we showed were able to achieve a fairly difficult postural task such as maintaining standing equilibrium in a changing gravitoinertial field, in spite of inaccurate geocentric and egocentric perceptions. Our results strengthen the idea that motor and cognitive representations are processed via parallel pathways. However, subjects interpreted the GIV as the gravity. This phenomenon was strengthened on the free pendulum support. Providing a support orthogonal to the gravitoinertial vector first favors well-balanced reaction forces repartition, second improves the accuracy to perceive the egocentric reference and gravitoinertial forces orientation to the detriment of the Earth-geocentric reference perception.

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